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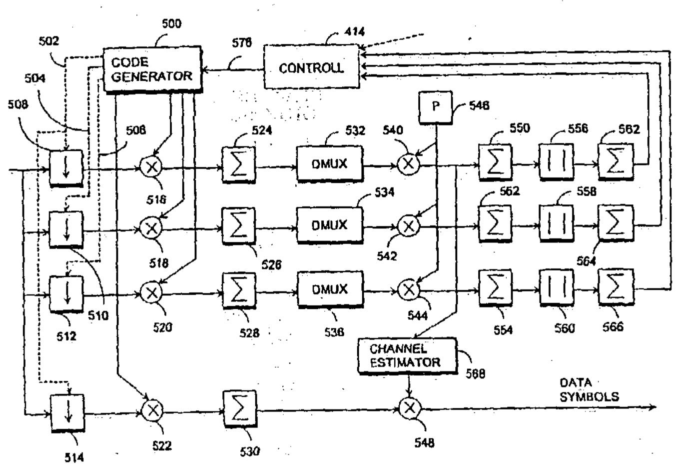
(54) Title: RECEIVER AND RECEPTION METHOD



(57) Abstract: A method for code tracking RAKE receiver fingers, in which method delay values have been set for the RAKE receiver fingers by using a code phase acquisition method. The method comprises taking several successive samples from a received signal, combining sample values measured in different fingers into measurement value sets, comparing the measurement value sets with each other and selecting the measurement value set having the highest value from among the measurement value sets meeting a minimum delay distance condition for the fingers, if any one of the sample values of the selected measurement value set is earlier than an on-time sample value determined on the basis of code phase acquisition, advancing the sampling and/or code phase of the particular finger, and if any one of the sample values of the selected measurement value set is later than an on-time sample value determined on the basis of code acquisition, delaying the sampling and/or code phase of the particular finger.

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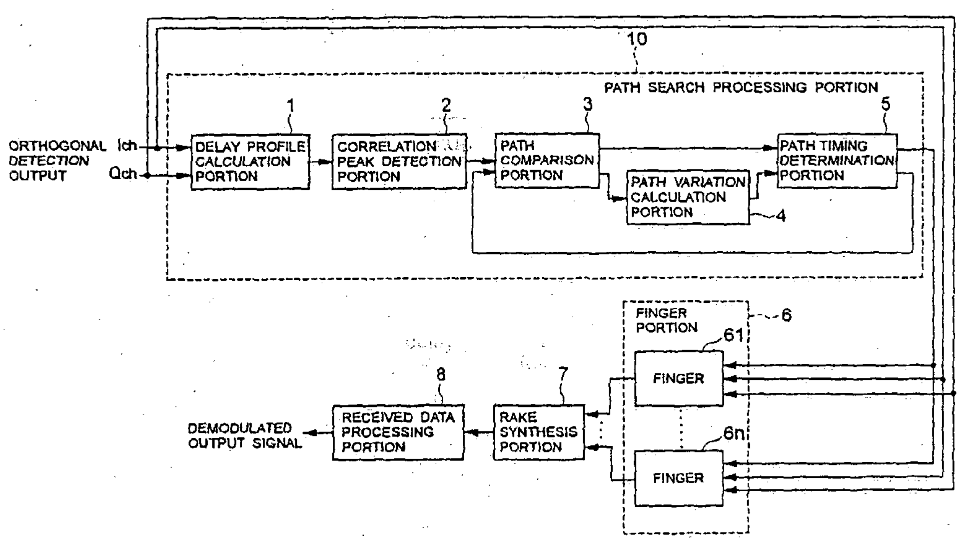
(54) Demodulation circuit for CDMA communications and demodulation method therefore

(57) A demodulation circuit for CDMA mobile communications systems prevents the degradation of reception qualities by selecting and assigning variation-free, stable paths out of received paths. When a delay profile is calculated based on received signals and those paths with a large power are selected from the delay profile and assigned to the finger portion, a path comparison portion detects whether one and the same path has been successively detected or not, and a calculation portion calculates the timing variation between currently detected path and previously detected path when one and the same path is detected successively, and a path timing determination portion assigns a new path to the finger portion in place of a path with a maximum variation if the variation of the path with a maximum variation within the paths already assigned to the finger portion has the variation larger than/equal to a variation threshold when a new path which is not assigned to the finger portion and of which level is higher than/equal to a predetermined assignment threshold is detected.

FIG. 1



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(54) CDMA Rake receiver detecting timing relation between fingers

(57) In a CDMA receiver operable in response to CDMA signals received through a plurality of paths to produce a reception signal, a path monitoring section detects whether or not selected and related paths among the plurality of the paths are identical with each other. When the selected and related paths are identical with each other, either one of the selected and the related paths for the CDMA signals alone is kept unchanged while another one of the selected and the related paths is released for reception of the other CDMA signals than the CDMA signals. In order to determine the identical path, detection is made about whether or not reception timing between the selected and the related paths has a close relation for a predetermined duration. In other words, the selected and the related paths are kept unchanged for the predetermined duration even when they are identical with each other.

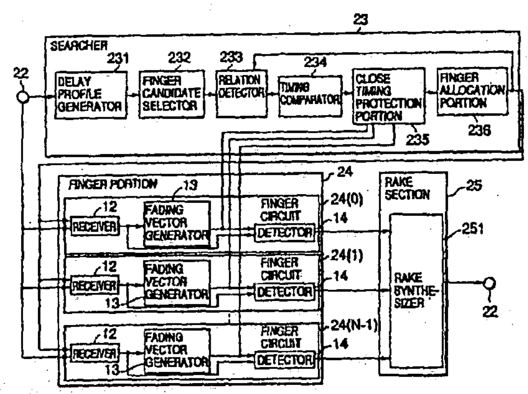

FIG.1

EP 0 984 561 A2

A Non-Coherent Tracking Scheme for the RAKE Receiver That Can Cope With Unresolvable Multipath

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***Abstract* — A novel non-coherent tracking technique for the RAKE receiver is introduced that has a good tracking performance even if multipaths cannot be resolved. Multiple chip-spaced correlators are used on unresolvable multipaths to provide estimates with uncorrelated noise. It is shown that the proposed tracker finds the pseudonoise code timing that maximizes the output of the maximal ratio combiner. The new tracking technique is easy to implement and does not require significantly more computations than conventional non-coherent time tracking techniques. The superior performance of the new tracking loop over conventional early-late time estimators in frequency-selective fading channels is demonstrated by means of computer simulations.**

I. Introduction

The RAKE receiver is a device well-suited for demodulating a spread spectrum signal in channels, where the signal bandwidth is much larger than the coherence bandwidth. The autocorrelation properties of a direct-sequence spread spectrum signal allow for using multiple correlators each of which uses a different time-shift to derive a different data estimate from the received multipath signal. By combining these estimates a better estimate is obtained than a single correlator can provide [1]. The performance of the RAKE receiver depends on the acquisition techniques, the assignment method for the correlators to the delays of the multipath components, the combining method of the correlator outputs, and the tracking capabilities of the receiver. The RAKE receiver typically contains a number of RAKE fingers. Each RAKE finger includes a correlator for retrieving the useful signal from a multipath, and a timing error estimator. The timing error estimate is used to control the local *pseudo-noise* (PN) generator such that the maximum signal power is obtained at the correlator output for the multipath the RAKE finger is assigned to. The goal of the RAKE receiver is to extract the most signal power out of the received signal, i.e., to maximize the signal-to-noise ratio (SNR) at the output of the combiner. For flat channels time tracking is achieved by using an early-late kind estimator [2, 3, 4, 5, 6, 7]. These tracking techniques can also be used to track signals in multipath when multipaths are resolvable.

The early-late tracking technique, however, does not perform satisfactory, if adjacent multipaths are unresolvable [8, 9]. In these scenarios, RAKE fingers are subject to increased time-jitter. Additionally, adjacent RAKE fingers, if tracking is performed independently, are likely to converge to the same relative delay. If the separation in time of the correlators is at the order of the chip duration or lower, the correlator outputs cannot be assumed independent and must be decorrelated prior to combining. Only recently research has been devoted to time tracking in frequency-selective fading environments. An approach based on extended Kalman filtering is first presented in [9] and further investigated in [10]. A RAKE receiver based on coherent tracking that does not require an extended Kalman filter is investigated in [11]. A non-coherent technique that subtracts an estimate of the multipath interference from the received signal before tracking is presented in [12]. In this paper, a tracking technique is proposed for the RAKE receiver that can cope and exploit unresolvable multipaths with little computational effort. It is shown that for a group of L equally spaced RAKE fingers the proposed technique finds the timing offset that maximizes the SNR at the output of the combiner provided that *maximal ratio combining* (MRC) is used. The tracking scheme is entirely non-coherent, thus, the receiver can be used for both coherent and non-coherent modulation techniques.

The paper is organized as follows. In Section II the system model is introduced. The RAKE receiver is introduced in Section 3. The performance of the suggested RAKE receiver is demonstrated in Section 4. Conclusions are presented in Section 5.

II. System Model and Illustration of the Problem

In this section the system model and the basic assumptions made for the subsequent analysis are introduced. Furthermore, a conventional non-coherent time tracking technique is reviewed and the problem of tracking in multipath is illustrated.

A. System Model and Basic Assumptions

Let the transmit signal $s(t)$ be

$$s(t) = \mathrm{Re}\{v(t)e^{j\omega_c t + \phi_c}\}, \tag{1}$$

where ω_c is the carrier frequency, φ some arbitrary phase offset, and $v(t)$ is the complex baseband signal to be transmitted.

$$v(t) = \sqrt{2P} \sum_{n=-\infty}^{\infty} c_n g_c(t - nT_c), \tag{2}$$

where c_n are the chips with $|c_n| = 1$. $g_c(t)$ is the pulse shaping filter response of a square root Nyquist filter (e.g. of a root raised cosine filter) with autocorrelation function

$$R_c(\tau) = \int_{-\infty}^{\infty} g_c^*(t) g_c(t + \tau)\, dt. \tag{3}$$

The noise $n(t)$ which is present at the receiver is

$$n(t) = \sqrt{2}[n_I(t)\cos(\omega_c t) - n_Q(t)\sin(\omega_c t)], \tag{4}$$

where $n_I(t)$ and $n_Q(t)$ are two independent zero-mean low-pass Gaussian processes with double-sided power spectral density (PSD) $\frac{N_0}{2}$ W/Hz. It is assumed that the received signal is passed through the receive filter and down-converted to baseband. The receive filter is a chip matched filter with impulse response $g_c^*(-t)$.

Furthermore, let $\xi(\tau)$ denote the channel impulse response of a *wide-sense stationary* channel with *p uncorrelated scatterers* (WSSUS),

$$\xi(\tau) = \sum_{i=1}^{p} \xi_i \delta(\tau - \tau_i). \tag{5}$$

$h(\tau)$ denotes the overall impulse response including transmit and receive filter, i.e.,

$$h(\tau) = \sum_{i=1}^{p} \xi_i R_c(\tau - \tau_i). \tag{6}$$

The received chip matched filtered baseband signal is

$$r(t) = \sqrt{2P} \sum_{n=-\infty}^{\infty} \sum_{i=1}^{p} c_n R_c(t - nT_c - \tau_i) e^{j\phi_c} + \tilde{n}(t), \tag{7}$$

where

$$\tilde{n}(t) = \sqrt{2}\left[\tilde{n}_I(t) + j\tilde{n}_Q(t)\right]. \tag{8}$$

$\tilde{n}_I(t)$ and $\tilde{n}_Q(t)$ are two independent zero-mean low-pass Gaussian processes with double-sided PSD $\frac{N_0}{2}|G(f)|^2$, and autocorrelation function $\frac{N_0}{2}R_c(\tau)$.

B. Illustration of the Problem

An example of a channel impulse response $\xi(\tau)$ consisting of three paths is shown in Fig. 1(a).

The corresponding $h(\tau)$ is also shown, where a root-raised cosine filter with 22 percent roll-off is used as a transmit filter and receive filter. Table I lists the delays and complex channel coefficients ξ_i. It is obvious that an early-late tracker with an offset $\Delta \leq T_c$ can be used to track the delays τ_i. Often $\Delta = \frac{T_c}{2}$ is used, but different choices for Δ have also been investigated (see e.g. [13]). An early late-tracker is shown in Fig. 2 and is often referred to as the *dot product discriminator* [14]. The received signal is correlated with the $\frac{T_c}{2}$-retarded and $\frac{T_c}{2}$-advanced code. Then the difference between the two correlation results is built. The channel phase dependency is removed by multiplying with the complex conjugate of the on-time signal. Note that the early and late correlators can be merged by correlating with the difference of the $\frac{T_c}{2}$-retarded and $\frac{T_c}{2}$-advanced code. In the implementation shown in Fig. 2 the received signal is chip matched filtered first, and then sampled at the chip rate. The real part of this product is the error signal ϵ which is passed through the loop filter to control the PN generator. Assuming a flat channel the structure for this tracker can be derived from the problem of maximizing the received power $P_s(\epsilon)$ of the on-time correlator, where ϵ is a small time offset between the received signal and the local PN code. The signal output power $\mathcal{P}_s$ of the on-time correlator is

$$\mathcal{P}_s(\epsilon) = 2P|\xi|^2 N_{\mathrm{PG}}^2 \left|R_c(\epsilon)\right|^2, \tag{9}$$

where N_{PG} is the *processing gain.* For $-T_c < \epsilon < T_c$ the necessary and sufficient condition for $\mathcal{P}_s$ to be a maximum is

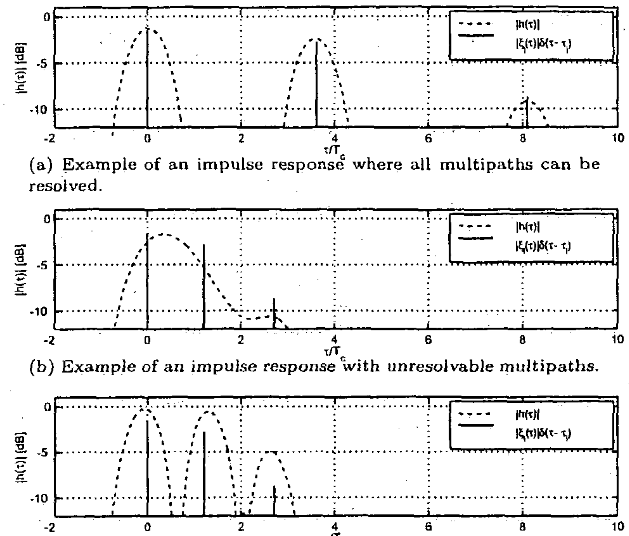
$$\frac{d}{d\epsilon}\mathcal{P}_s(\epsilon) = 0. \tag{10}$$

The derivative of (9) with respect to ϵ is

$$\begin{aligned}\frac{d}{d\epsilon}\mathcal{P}_s(\epsilon) &= 4PN_{\mathrm{PG}}^2|\xi|^2 R_c^*(\epsilon)\,\frac{d}{d\epsilon}R_c(\epsilon)\\ &= 4PN_{\mathrm{PG}}^2|\xi|^2 R_c^*(\epsilon)\lim_{\delta\to 0}\frac{R_c(\epsilon+\delta)-R_c(\epsilon-\delta)}{2\delta}.\end{aligned} \tag{11}$$

The first term of (11) is identified as the complex conjugate of the on-time correlation signal. The limit can be well approximated by the divided differences

$$\lim_{\delta\to 0}\frac{R_c(\epsilon+\delta)-R_c(\epsilon-\delta)}{2\delta} \approx \frac{R_c(\epsilon+\Delta)-R_c(\epsilon-\Delta)}{2\Delta} \tag{12}$$



(a) Example of an impulse response where all multipaths can be resolved.

(b) Example of an impulse response with unresolvable multipaths.

(c) Same example as (b), but with different phases.

Fig. 1. Examples of impulse responses where multipath can and cannot be resolved.

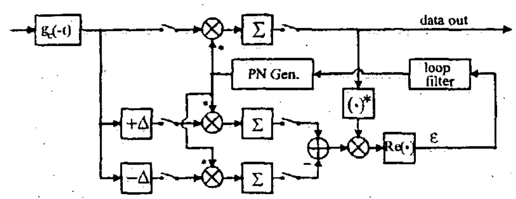


Fig. 2. Early-late tracker with on-time correlation.

Table I. Delays and channel coefficients used in the examples

	(a)			(b)			(c)		
i	τ_i/T_c	$\mathrm{Re}\{\xi_i\}$	$\mathrm{Im}\{\xi_i\}$	τ_i/T_c	$\mathrm{Re}\{\xi_i\}$	$\mathrm{Im}\{\xi_i\}$	τ_i/T_c	$\mathrm{Re}\{\xi_i\}$	$\mathrm{Im}\{\xi_i\}$
1	0.0	0.834	0.000	0.0	0.834	0.000	0.0	0.834	0.000
2	3.6	0.731	0.012	1.2	0.731	0.012	1.2	-0.731	-0.012
3	8.1	0.346	-0.122	2.7	0.346	-0.122	2.7	0.346	-0.122

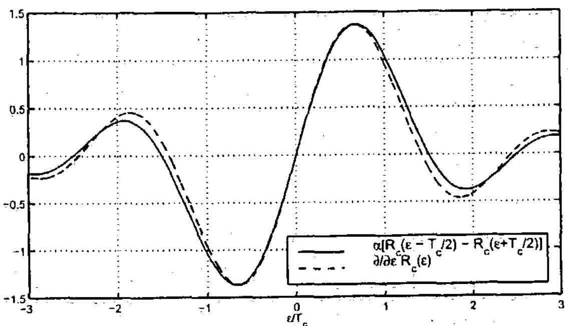


Fig. 3. Derivative and divided differences for a raised cosine impulse with 22% roll-off.

which is obtained by multiplying with the difference code. For a raised cosine impulse with 22 percent roll-off and for $\Delta = T_c/2$ the derivative and its approximation using the divided differences is shown in Fig. 3. An analysis of the open and closed loop performances for this tracker is given in [7].

The noise at the correlator outputs at the path delays of Fig. 1(a) can be assumed to be uncorrelated, and thus, MRC can be used. For a root-raised cosine filter with 22 percent roll-off, for $|\tau| > 0.85T_c$, the magnitude $|R_c(\tau)|$ is less than 14 dB, i.e., for the corresponding pair of transmit and receive filters the correlator noise can be practically assumed uncorrelated, if all $|\tau_i - \tau_j| \geq 0.85T_c$ with $i \neq j$ and $1 \leq i, j \leq p$. For $|\tau_i - \tau_j| = nT_c$, n integer, $n \neq 0$, the noise is exactly uncorrelated, since $R_c(nT_c) = 0$.

A channel impulse response for which multipath cannot be resolved is shown in Fig. 1(b), where the coefficients are kept the same as in Fig. 1(a), but the relative delays are reduced to one third of the original delays. If multiple RAKE fingers are originally assigned to this channel profile, and tracking is performed independently for each RAKE finger, each RAKE finger finds the maximum correlation peak at $0.35T_c$. Obviously, for delay differences $|\tau_i - \tau_j| < T_c$ for $1 \leq i, j \leq p$, $i \neq j$, adjacent RAKE finger outputs cannot be assumed uncorrelated. Decorrelating the RAKE fingers by multiplying with the inverse correlation matrix is possible, but a substantial amount of computations is required. The condition of the correlation matrix becomes worse the closer RAKE fingers get in time. An ill-conditioned matrix can lead to stability problems and performance degradation. Conventionally, a controller merges RAKE fingers, if the delay difference becomes smaller than a minimum spacing, i.e., the RAKE finger that detects the strongest path remains, and the RAKE finger that detects the weaker path is taken out of the detection process.

If just one RAKE finger is assigned to extract the signal of the impulse response of Fig. 1(b), the receiver loses signal power. Furthermore tracking is distorted by multipath. Typically, phases and magnitudes of the channel coefficients ξ_i are varying considerably faster than the relative delays τ_i of the multipaths. If multipaths cannot be resolved, adjacent paths add constructively or destructively to the overall channel impulse response which results in rapidly changing positions of the peaks. Thus, the RAKE finger is subject to an increased time jitter. To illustrate this behavior the phase of the channel coefficient ξ_2 is altered by π, and the resultant channel impulse response is plotted in Fig. 1(c). Tracking loop parameters such as loop bandwidth, etc., are designed to track the delay variations of a particular path but not the fast fading characteristics. If the Doppler bandwidth exceeds the loop bandwidth, then further degradation of the performance can be expected due to the lacking ability of the tracker to adopt to the fast varying channel.

III. A Tracking Scheme That Can Cope and Exploit Unresolvable Multipath

The tracking loop that can cope and exploit unresolvable multipath consists of a number of RAKE fingers which contain a correlator to derive the on-time estimate r_i and a time tracking error estimator of the type shown in Fig. 2. If multipath spacing is large compared to the chip period, these RAKE fingers can track the correlation peaks independently. If multipath spacing is at the order of the chip duration or smaller, a group of equally-spaced RAKE fingers is assigned to these paths, where the RAKE finger spacing is the minimum RAKE finger spacing allowed in the RAKE receiver. Tracking is then carried out jointly for this group to find the optimum PN offset while keeping the relative finger spacing fixed to the minimum spacing. For the time being the minimum spacing is the chip period T_c which yields uncorrelated estimates r_i easily allowing for MRC. Different RAKE finger spacings with spacings less than T_c are subject to ongoing research. In any case, a controller insures that during tracking the spacing between RAKE fingers never becomes smaller than the minimum allowed spacing for the RAKE. If the spacing between two fingers (or one finger and a group of fingers) that has originally been large with respect to T_c, has decreased to a spacing equal to the minimum spacing these fingers are grouped and tracking is then carried out jointly for that group. It is shown in the following that by using the early-late estimator of Fig. 2 the error signal to control a group of L fingers is simply obtained by adding the error estimates of the fingers that form the group.

Analysis

The i-th complex channel coefficient h_i seen by the i-th RAKE finger, $0 \leq i \leq L-1$, is obtained by sampling $h(\tau)$ at $iT_c + \epsilon$, where ϵ is the sampling offset to be optimized,

and

$$h_i(\epsilon) = h(iT_c + \epsilon). \tag{13}$$

Since the noise power is constant on each RAKE finger, the task of the tracker is to find the sampling phase that maximizes the output signal power. The signal power $\mathcal{P}_s(\epsilon)$ at the combiner output is directly proportional to the sum of all squared magnitudes of the channel coefficients, i.e.,

$$\mathcal{P}_s(\epsilon) = c \sum_{i=0}^{L-1} |h_i(\epsilon)|^2, \tag{14}$$

where c is a constant. The necessary condition for $\mathcal{P}_s(\epsilon_o)$ to be maximum is that the derivative of $\mathcal{P}_s$ at ϵ_o is zero. The derivative of (14) with respect to ϵ is

$$\begin{aligned} \frac{d}{d\epsilon}\mathcal{P}_s(\epsilon) &= c \sum_{i=0}^{L-1} h_i^*(\epsilon) \frac{d}{d\epsilon} h_i(\epsilon) \\ &= c \sum_{i=0}^{L-1} h_i^*(\epsilon) \lim_{\delta \to 0} \frac{h_i(\epsilon+\delta) - h_i(\epsilon-\delta)}{2\delta}, \end{aligned} \tag{15}$$

where the limit can be approximated by the divided differences,

$$\lim_{\delta \to 0} \frac{h_i(\epsilon+\delta) - h_i(\epsilon-\delta)}{2\delta} \approx \frac{h_i(\epsilon+\Delta) - h_i(\epsilon-\Delta)}{2\Delta}. \tag{16}$$

However, (15) is the sum of all error estimates over all RAKE fingers. Hence, it can be concluded that the sum of all error signals of the RAKE fingers within a group of L RAKE fingers is the desired error signal for adjusting the group of fingers.

If the Doppler bandwidth is much greater than the loop filter bandwidth, the RAKE fingers cannot follow the channel. The optimum timing offset $\bar{\epsilon}_0$ then is the timing offset that maximizes the *average* output power at the output of the combiner. The derivation for average power is analogous to the above, and it can be shown that, likewise, the sum of all error estimators within a group is the desired error criterion for adjusting the timing offset for that group.

For a group of L fingers, the conceptual block diagram of the proposed RAKE receiver *after grouping the fingers* is shown in Fig. 4. For this group, the combined error signal is passed through the common loop filter which output controls the PN code generator for the group.

IV. Performance Evaluation

A coherent direct-sequence spread spectrum system has been implemented on a computer to demonstrate the performance of the proposed tracking technique. The system uses QPSK modulation with a chip rate of 4.096 MHz and a processing gain of 256. Eight pilot bits are periodically inserted every 0.625 ms from which all tracking information is derived. For the channel model a six tap Rayleigh fading model with the classical Doppler spectrum

$$|S(f_d)|^2 = \begin{cases} \dfrac{1.5}{\pi f_{d,\max}\sqrt{1-\left(\frac{f_d}{f_{d,\max}}\right)^2}} & \text{for } |f_d| < f_{d,\max}, \\ 0 & \text{otherwise}, \end{cases} \tag{17}$$

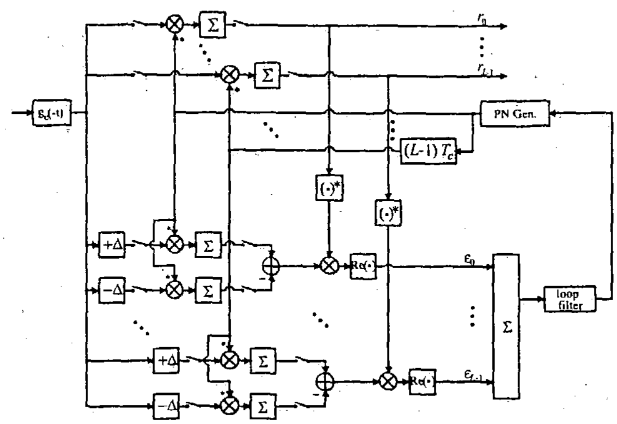


Fig. 4. Conceptual block diagram of the RAKE that can exploit unresolvable multipath.

Table II. Channel model

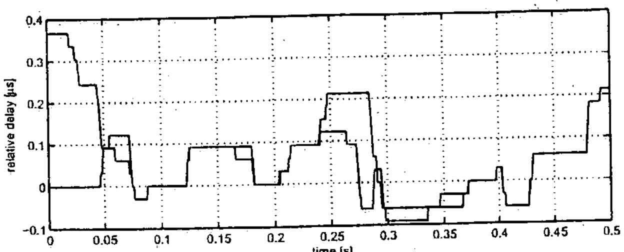
rel. delay [ns]	avg. path power [dB]	Doppler spectrum
0	0	classic
200	-0.9	classic
800	-4.9	classic
1200	-8.0	classic
2300	-7.8	classic
3700	-23.9	classic

is used.

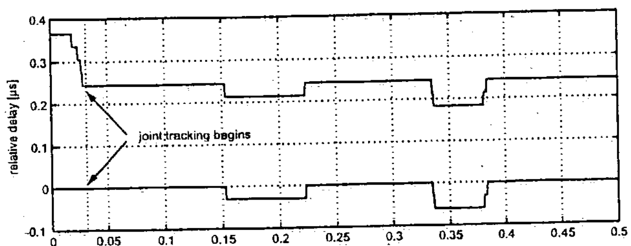
Table II summarizes the channel model delay parameters and average path strengths. Since the chip duration is 244 ns, it is evident that the first two paths of the channel model are unresolvable.

Simulations are carried out for both the conventional and the proposed method using an SNR/bit of 0 dB. The maximum Doppler frequency is set to 93 Hz corresponding to 50 km/h for a carrier frequency of 2 GHz. Two RAKE fingers are assigned to the first two multipaths with an initial relative delay of 0 ns and 366 ns, respectively. The relative delays of both fingers for the conventional RAKE receiver and the proposed RAKE receiver are shown in Fig. 5(a) and Fig. 5(b), respectively. It can be seen from Fig. 5(a) that without a joint tracking scheme, the RAKE fingers converge shortly to the same relative delay. Although the delay of the multipaths is fixed in the channel model, the relative delays of the fingers varies considerably between -100 ns and 200 ns, since the tracker which is optimized for flat channels is distorted by multipath. The same simulations are run using the proposed tracking scheme, i.e., RAKE fingers are grouped once their spacing becomes equal to the minimum spacing. The results are shown in Fig. 5(b). Once the RAKE fingers are grouped (after about 33 ms) tracking is performed jointly. The joint tracking keeps both fingers around both multipaths. Since they are separated by the chip spacing, both correlators can obtain different signal estimates with uncorrelated noise from the multipaths.

For the same Doppler spread and the same channel model, bit error simulations have been carried out to further evaluate the performance. The conventional RAKE receiver uses only two paths, one for the first two multi-



(a) Conventional tracker, 0 dB SNR/bit.



(b) Proposed tracking technique, 0 dB SNR/bit.

Fig. 5. Time tracking of RAKE fingers.

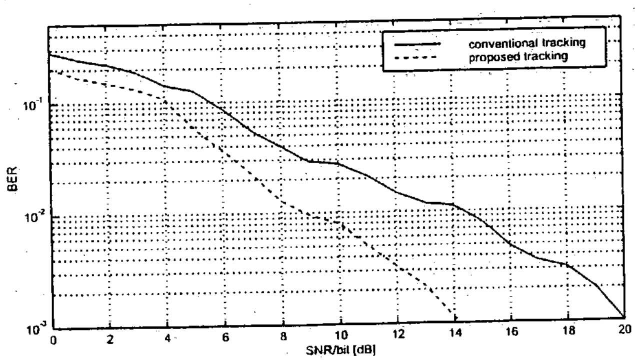


Fig. 6. Performance comparison of conventional tracking vs. the proposed tracking scheme.

paths and the other for the third multipath. The proposed receiver can use two fingers on the first two paths, and it uses a third RAKE finger for the third path. It is assumed that the remaining multipaths are not utilized by the RAKE receivers.

Results of these simulations are shown in Fig. 6. This figure shows the uncoded bit-error rate (BER) over different SNRs. For BERs of 1×10^{-3} a gain of more than 5 dB of the proposed RAKE that uses an additional RAKE finger on the first two paths over the conventional RAKE that only uses one RAKE finger for the unresolvable paths can be observed. The performance difference can be attributed to two reasons. First, the proposed receiver can utilize one finger more than the conventional receiver, and thus can pick up more power of the received signal. Second, the tracking of the first RAKE finger is distorted by multipath. Errors occur, if tracking has moved the finger away from the signal, or the channel has changed faster than the tracker can follow.

V. Conclusions

A novel non-coherent time tracking scheme has been presented which is especially designed to track the relative delays of RAKE fingers which are assigned to adjacent unresolvable multipaths. The proposed technique is based on a specific non-coherent tracking technique which only requires one additional correlator for each RAKE finger. The computational complexity of the proposed tracking scheme is about the same as for conventional time tracking. Simulations confirm the superior tracking capabilities of the proposed technique over conventional techniques, where a single correlator is used to track the peak of an agglomeration of narrow-spaced multipaths.

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